# CONDITION ASSESSMENT OF HIGH VOLTAGE POWER TRANSFORMER USING DISSOLVED GAS ANALYSIS


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# CONDITION ASSESSMENT OF HIGH VOLTAGE POWER TRANSORMER USING DISSOLVED GAS ANALYSIS

*A Thesis submitted in partial fulfillment of the requirements for the degree of*

*Bachelor of Technology* in "Electrical Engineering"

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# CERTIFICATE

This is to certify that the thesis entitled "**Condition Assessment of High Voltage Power Transformer Using Dissolved Gas Analysis**", submitted by **Debashis Ranjan Patra (Roll. No. 109EE0295) and Sonal Sagar Boda (Roll. No. 109EE0036)** in partial fulfilment of the requirements for the award of **Bachelor of Technology** in **Electrical Engineering** during session 2012-2013 at National Institute of Technology, Rourkela. A bonafide record of research work carried out by them under my supervision and guidance.

The candidates have fulfilled all the prescribed requirements.

The Thesis which is based on candidates' own work, have not submitted elsewhere for a degree/diploma.

In my opinion, the thesis is of standard required for the award of a bachelor of technology degree in Electrical Engineering.

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# ABSTRACT


Condition monitoring is the process, which is used to monitor parameter of condition in machinery, such that if a significant change occurs it indicates that it may lead to failure of that machine. It is a major component of predictive routine maintenance. The use of conditional monitoring allows maintenance to be done in a scheduled manner or some other actions are to be taken to avoid the aftermaths of failure, before it leads to occurrence of any severe failure.

Dissolved Gas Analysis (DGA) is a widely used technique to estimate the condition of oil-immersed transformers. The experimental results of the level and the change in concentration of different combustible gases in the insulating oil is a trustworthy diagnostic tool which can be used as indicator of undesirable events occurring inside the transformer, such as hot spots, electrical arcing or partial discharge. The objective of this paper is mainly to analyse available data from DGA, and investigate data that may be useful in quantitative modelling of the transformer's reliability.

Dissolved Gas Analysis (DGA) of transformer oil is the best indicator of a transformer's overall condition. It will provide useful information about the condition of oil and help to identify the type of fault in the transformer.

Depending upon the location of a transformer, its rating and the nature of its usage, some dissolved gas analysis is to be scheduled which will be appropriate for that transformer. The more critical the unit is the more frequently it should be sampled. Hence DGA is mainly performed in Power transformers.

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# CHAPTER 1

# INTRODUCTION

## 1.1 Motivation

Power transformers play an important role in both the transmission and distribution of electrical power. Since a fault in a transformer can have a huge repercussion when failures occur, and as the number of old transformers and of those that are difficult to operate in overload conditions is on the rise, it is important to detect incipient faults in a transformer and forecast and prevent failures [17]. In operation, transformers are subject to electrical and thermal stresses, which can cause the degradation of the insulating materials. Generally the degradation products are gases, which will get dissolve in the oil entirely or partially. In the oil these gases are easily detected at the ppm level by dissolved gas analysis.

Dissolved gas analysis (DGA) is a widely used most powerful method to detect incipient faults on oil filled electrical equipment [16]. The electrical equipment may be a transformer, a load tap changer or a cable.

Dissolved Gas Analysis (DGA) of transformer oil is the best indicator of a transformer's overall condition. Hence this widely accepted method is used in routine maintenance of power transformers [18]. Transformer oils perform at least four functions for the transformer. Oil provides insulation, provides cooling, and helps extinguish arcs. Oil also dissolves the gases which are generated due to degradation of oil, moisture and gas from insulation, deterioration of cellulose, and gases and moisture from the surrounding the oil is exposed to. Any deterioration in the oil can lead to premature failure of the equipment. The most common type of oil used in transformers is of a mineral oil origin.

When the mineral oil is subjected to high thermal and electrical stresses, it decomposes and, as a result, gases are generated. Different types of faults will generate different gases, and the chemical analysis of these gases, performed through a procedure called DGA (Dissolved Gas Analysis), will provide useful information about the condition of the oil, and help to identify the type of fault in the transformer.

DGA is performed accordance with ASTM D3612 or IEC 60567. There are different types of faults which can be detected by DGA. The details about the faults are explained below.

## 1.2 Types of Faults detectable by DGA

There are 7 types of faults which can be detected using DGA methods which are described below. Duval triangle is one of the methods to detect faults. There are some no. of subdivisions of faults to certain kinds of faults which can be detected by new version of Duval triangle method [16].The main faults are;

- Partial Discharge (PD)
- Discharges of Low energy (D1)
- Discharges of High energy (D2)
- Thermal fault, $\mathrm{T} < 300\ ℃$ (T1)
- Thermal fault, $300 < T < 700\ ℃$ (T2)
- Thermal fault, $\mathrm{T} > 700\ ℃$ (T3)
- Thermal & Electrical fault (DT)

*Partial Discharge (PD):* The temperature plays a less important role in the chemical reaction occurring in the PD since the vapour temperature in the discharge zone is not higher than 60-150°C. Hydrocarbon cracking in the partial discharges occurs as a result of excitation of molecules and their subsequent dissociation by collision with high energy electrons, atomic hydrogen, ions and also free radicals. It often generates large amounts of hydrogen. Example: Discharges of the cold plasma (corona) type in gas bubbles or voids, with the possible formation of X-wax in paper.

*Discharges of Low energy (D1):* Partial discharges of the sparking type, inducing pinholes, carbonized small punctures in paper. Low energy arcing results in surface tracking of paper or the formation of small amount of carbon particles in oil.

*Discharges of High energy (D2):* Discharges in paper or oil, with power follow-through, resulting in extensive damage to paper or large formation of carbon particles in oil, metal fusion, tripping of the equipment and gas alarms.

*Thermal fault (T1):* These types of faults occur below $300\ ℃$. These are evidenced by paper turning brownish (> 200 °C) or carbonized (> 300 °C).

*Thermal fault (T2):* These types of faults occur in between 300 ℃ to 700 ℃ . These are evidenced by carbonization of paper, formation of carbon particles in oil.

*Thermal fault (T3):* The high temperature faults whose temperature is more than 700 ℃ falls in this kind of fault. These are evidenced by extensive formation of carbon particles in oil, metal coloration (800 °C) or metal fusion (>1000 °C).

*Thermal & Electrical fault (DT):* Sometime both thermal and electrical fault occurs inside the transformer. These faults accelerate the decomposition of dielectric fluid and solid insulation.

## 1.3 Organization of Thesis

***Chapter 1:*** This chapter reviews the literature concept of dissolved gas analysis. It describes different types of faults detectable by DGA and its requirement.

***Chapter 2:*** It describes the mechanism of gas generation. The normal limits and critical limits of concentration of different gases are shown in this chapter.

***Chapter 3:*** This chapter describes different techniques of detection of dissolved gases like oil sample collection, extraction of dissolved gases and its detection.

***Chapter 4:*** This chapter describes about the incipient fault detection techniques of power transformers using different diagnostic tools after getting concentration of the dissolved gases using different methods like key gas method, ratios method and Duval triangle method.

***Chapter 5:*** This chapter reviews novel methods of fault detection using different modern instruments which gives more accurate results in less time.

***Chapter 6:*** In this chapter a latest diagnostic method for fault detection, Extension to the Duval triangle has been discussed. It gives an idea about more specific fault.

***Chapter 7:*** This chapter analyses the software analysis with the practical data and compares both the results for more accuracy of the fault detection.

***Chapter 8:*** This chapter summarizes the results obtained in various chapters and gives an idea about the scope for future work.

# CHAPTER 2

# MECHANISM OF GAS GENERATION IN POWER TRANSFORMERS

## 2.1 Introduction

The cause of gas generation is the breaking of the chemical bonds between the atoms that make up the hydrocarbon molecules of the mineral oil. The faults in the transformer produce the energy that is needed for breaking the chemical bonds [3]. The gases generated include hydrogen $(H_2)$, methane $(CH_4)$, ethane $(C_2H_6)$, ethylene $(C_2H_4)$, acetylene $(C_2H_2)$, carbon dioxide $(CO_2)$ and carbon monoxide $(CO)$.The gases listed above are generally referred to as key gases.

Lower amounts of energy or lower temperatures are required to create or break the C-H molecular bonds. Higher amounts of energy or higher temperatures are needed, to create, or break C-C molecular bond. In the ascending order the energy required for make or break the bonds are; C-C single bonds, C=C double bonds and C≡C triple bonds [3].

All of the gases are formed because of the degradation of the oil itself except carbon monoxide and oxygen,. Carbon monoxide, carbon dioxide ($CO_2$), and oxygen are formed from degradation of paper insulation which is made up of cellulose. Carbon dioxide, oxygen, nitrogen ($N_2$) and moisture can also be absorbed from the air if somehow oil is in contact with atmospheric air which may happen due to leakage in the tank of transformer.

## 2.2 Normal and Action limits of dissolved gas

When mineral oil contains normal values of dissolved gas, it indicates no incipient fault in the transformer. As the value exceeds the normal limit, sample frequency should be increased because exceeding the normal limit indicates some small kind of faults inside the transformer. Before the fault becomes critical some supplementary actions have to be taken so as to avoid critical faults of other equipment. As the value exceeds the action limit, that means some critical situation has arrived and removal of transformer from service should be considered [3].

The table for the different limits is derived from information provided within ANSI/IEEE C57.104 [10]. It gives concentration of all the gases in ppm level. Based on these values necessary steps should be taken place.

The normal and action limits of dissolved gases in the oil are given below in Table 2.1.

**Table 2.1:** Normal and action limits of dissolved gases [7]

| Gas | Normal Limits (ppm) | Action Limits (ppm) |
|---|---|---|
| Hydrogen ( $H_2$ ) | 150 | 1000 |
| Methane ( $CH_4$ ) | 25 | 80 |
| Ethylene ( $C_2H_4$ ) | 20 | 150 |
| Acetylene ( $C_2H_2$ ) | 15 | 70 |
| Ethane ( $C_2H_6$ ) | 10 | 35 |
| Carbon dioxide( $CO_2$ ) | 10000 | 15000 |
| Carbon monoxide ( $CO$ ) | 500 | 1000 |

# CHAPTER 3

## DETECTION TECHNIQUES OF DISSOLVED GASES

The DGA technique detects gas in parts per million (ppm) dissolved oil by the use of gas extraction unit and a gas chromatograph. The DGA analysis is performed in three steps:

1. Collection of Oil sample
2. Extraction of gases from the oil
3. Detection of gases

### 3.1 Collection of oil sample

The oil sample collection is carried out using different apparatus and methods. The most appropriate container is a gas-tight glass syringe of capacity 150 ml or 250 ml and fitted with three way Teflon valves. The oil should retain and transport the sample of transformer oil in the same condition as it is inside a transformer with all fault gases dissolved in it. Attention to cleanliness is the key to success.

Oil samples shall be taken from the main oil stream: points outside the main oil stream shall be disregarded. This point should be located in a place where a live oil sample can be collected rather than in an area where the oil is static.  To prevent oxidation the samples shall be shielded from direct light by wrapping the container in aluminium foil or by storing in an opaque enclosure.

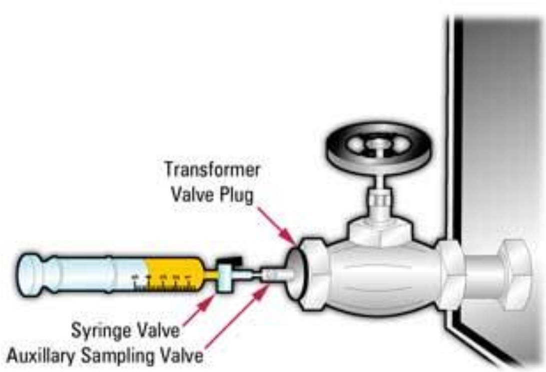



Figure 3.1: Oil sampling by syringe

The procurement of representative oil samples from a transformer is very important and the sample should be collected and transported in such a way that the gases dissolved in the oil are not subject to any changes like quantity and composition. Directly exposure to air and prolonged exposure to the light is avoided. Hence sample should be kept in light-proof containers until the start of testing [19]. Sampling taken by syringe is probably the most popular technique although other techniques are also available.

Oil samples are usually taken at the bottom of the tank, from the drain valve, but also for special purposes, at the top from the radiators, or the gas relay. The filled syringe is then sent to the laboratory for analysis which involves extraction of gases from the oil sample and detection of gases [1].

Three samples have been collected. After doing the DGA process of those oils, gas concentrations are found out. The transformers from which oils have been collected are;

- MSDS2/Transformer # 2 (132 kV/33 kV, 63 MVA)
- CRM Transformer # 53 (33 kV/7.1 kV, 16 MVA)
- Tandem mill rectifier transformer # 4 (33 kV/7.1 kV, 16 MVA)

## 3.2 Extraction of gases from the oil

After collecting a sample the important step is the extractions of gasses from the oil unless complete extraction can be achieved the results obtained cannot be relied upon. Removing the gas from the oil is one of the more difficult and critical portions of the procedure. Considerable difficulties can be encored in procuring assembly should fulfil the following given conditions;

- High vacuum must be must be used throughout the apparatus.
- The design of the apparatus must be done in such a way that it must be checked carefully that vacuum collection ratio is achieved for the given sample [1].

The most interest presents the variant with heating up to 125°C. The gas diffuses in preliminary vacuum vessel during the draining of oil layer from the insertion point to the storage flask. The processes of gas diffusion and flow one should considered separately.

## 3.3 Detection of gases

Gas detection methods may be split into two groups, (i) direct methods, which monitor a physical parameter of the target gas, and (ii) indirect methods, which use a chemical reaction or indicator to show the concentration of the gas being sensed. This review will predominantly focus on direct method of gas detection techniques.

In transformer oil analysis, the technique is used to determine the concentrations of dissolved gases within the oil sample after extracting the gases from the sample, which can be used with gas analysis and other methods to evaluate electrical faults within a transformer or oil insulated electrical components.

There are two methods for detection of gases dissolved in the oil sample such as;

- Gas chromatography (GC)
- Optical gas detection

### *3.3.1 Gas chromatography (GC)*

The 1st one Gas chromatography (GC) is one of the most widely used techniques in modern analytical chemistry [1]. Generally, GC is used to separate different complex mixtures of different molecules based on their physical properties, such as polarity and boiling point. It is an handy tool to analyse gas and liquid samples containing many thousands of different molecules, allowing the analyst to identify both the types of molecular species present and their concentrations also.

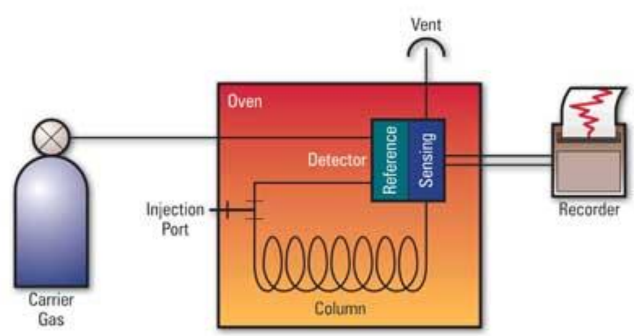



Figure 3.2: Gas Chromatography Instrument

In gas-liquid chromatography, it is the interaction between the gaseous sample (the mobile phase) and a standard liquid (the stationary phase), which causes the separation of different molecular constituents. The stationary phase is either a polar or nonpolar liquid, which, in the case of capillary column, coats the inside of the column or is impregnated onto an inert solid that is then packed into the GC column. The gas is identified by an appropriate detector whose output is recorded on a chart in the form of peaks. Normally Thermal Conducive detectors (TCD) type detectors are used for this process. Each gas peak corresponds to a different constituent of the original gas mixture. The gas chromatographic apparatus consist of a gas steam supplied by gas cylinder a sample injection port, a chromatographic column a detector and a strip chart recorder. A Chromatogram is the plot of the detector response which measures the change of composition of the column effluent against time or volume of the carrier gas.

This method is very accurate and highly selective means of detecting concentration. But the disadvantages are this method is very expensive, not easy to use on-line, as gas sampling necessary.

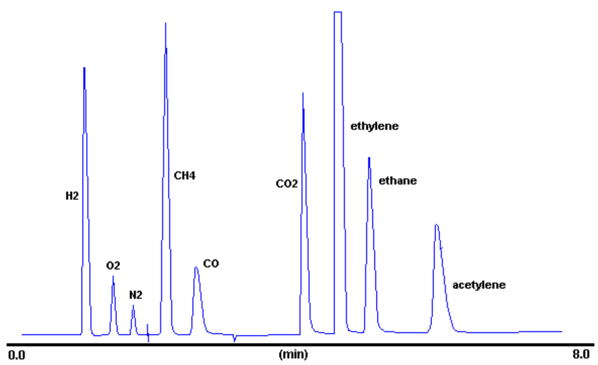



Figure 3.3: A Typical Gas Chromatogram

### *3.3.2 Optical gas detection*

Optical gas detection method is generally known as optical-fibre remote correlation techniques. This includes a discussion of differential methods utilizing dual wavelength operation. Inaba suggested the use of a dual-wavelength laser to realize a differential absorption method that could be used over many kilometers of low-loss optical fibre, provided that suitable gas absorption bands are present.

This typically involves the comparison of the received power at two or more different wavelengths, each having passed through a remote gas cell, so that the differential absorption of the gas sample could be used to infer the concentration of the target gas.

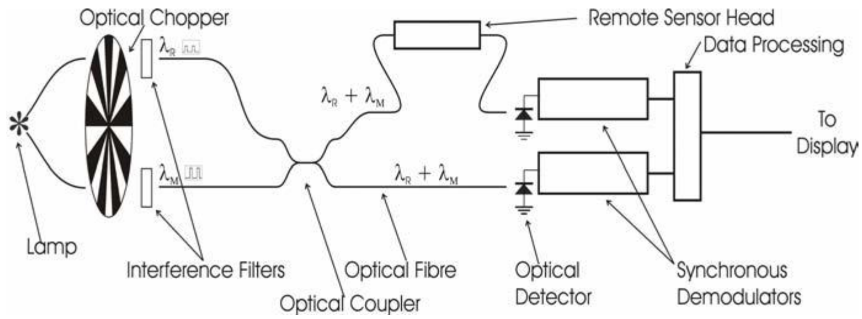



Figure3.4: Schematic of a differential fibre-optic detection system

# CHAPTER 4

# DIAGNOSTIC METHODS OF DISSOLVED GASES

Different types of DGA methods have been implemented in order to determine the fault in a transformer which are analysed as follows;

- Key gas method
- Ratios methods or Basic gas ratios method and
- National Standard's method
- Duval Triangle method

## 4.1 Key gas method

Various faults produce certain gases and the percent of some gases have been found to indicate fault types, such as overheated oil and cellulose, corona in oil and arching in oil. The diagnostic interpretations applying various gases are given below in the Table 4.1.

**Table 4.1:** Fault Indicator gases [8]

| Gas detected | Primary Interpretation | Secondary Interpretation |
|---|---|---|
| Hydrogen ($H_2$) | Corona effect | Arcing, overheated oil |
| methane ($CH_4$) | | Arcing, serious overheated oil |
| ethane ($C_2H_6$) | | Thermal fault like Corona & overheated oil |
| ethylene ($C_2H_4$) | Thermal fault, local or overheated oil | Corona, arcing |
| acetylene ($C_2H_2$) | Electric fault like arcing and sparking | Severely overheated oil |
| carbon monoxide ($CO$) | Overheated cellulose decomposition | Arcing if fault involves cellulose |
| carbon dioxide ($CO_2$) | Cellulose decomposition | |
| Oxygen ($O_2$) & Nitrogen ($N_2$) | Indicator of system leaks over pressurization or changes in temperature. | |

### 4.2 Ratios methods or Basic gas ratios method

The “Basic Gas ratios” recognized in the International Electro technical Commission (IEC) standards is equivalent to Doernenberg ratios and Rogers ratios in the ANSI/IEEE C57.104.

Three gas ratios are used in DGA methane/hydrogen, acetylene/ethylene, and ethylene/ethane. Faults often start as incipient, low energy faults which may develop into more serious higher energy or higher temperature faults. When a fault is detected, it is important to determine the trend in the rate of increase of the gas. An increase in gas values of more than 10% per month above the normal values will indicate that the fault is active. It is also important to determine the trend in the occurrence of different types of faults, and to detect early, any deterioration towards a more serious fault. Determining the trend in both the rate of increase of the individual gases, and the occurrence of different types of faults, will provide information on the health of the transformer.

**Table 4.2:** IEC Gas ratio [3]

| Case | Characteristics fault | acetylene/ethylene | methane/hydrogen | ethylene/ethane |
|---|---|---|---|---|
| PD | Partial Discharge | NS | < 0.1 | < 0.2 |
| D1 | Discharges of Low energy | > 1 | 0.1 - 0.5 | > 1 |
| D2 | Discharges of High energy | 0.6 - 2.5 | 0.1 - 1.0 | > 2 |
| T1 | Thermal fault, $T < 300$ ℃ | NS | > 1 | < 1 |
| T2 | Thermal fault, $300 < T < 700$ ℃ | < 0.1 | > 1 | < 1 |
| T3 | Thermal fault, $T > 700$ ℃ | < 0.2 | > 1 | > 4 |

NS – No Significance

The ratio of $CO_2/CO$ is sometimes used as an indicator of the thermal decomposition of cellulose. The rate of generation of $CO_2$ typically runs 7 to 20 times higher than $CO$. Therefore, it would be considered normal if the $CO_2/CO$ ratio were above 7. If the $CO_2/CO$ ratio is 5 or less, there is probably a problem. If the $CO_2/CO$ ratio is 3 or under with increased furans it indicates severe and rapid deterioration of cellulose is occurring and consideration should be given for taking the transformer out of service for further inspection [7] .

### 4.3 National Standard's method

In this Standard four-levels of criteria have been developed to determine the risks of the transformers. These criteria help to determine whether a transformer is behaving normally, especially when there is no previous dissolved gas history or the transformers have been under operation for many years. The criterion uses total concentration of all combustible gases presented in Table below for the type of Generator Step-Up (GSU) Transformers and Grid Transformers separately. The transformer is considered "Normal" when the total dissolved combustible gas (TDCG) is below or within levels and also when any individual combustible gas does not exceed specified levels.

**Table 4.3:** Condition vs. operation time of the transformer [6]

| Condition | Concentrations of the total combustible gas (ppm) | | | |
|---|---|---|---|---|
| | Type | Operation time of the transformer | | |
| | | <8 year | 8….15 year | >15 year |
| $V_0$ – Normal | GRID | <350 | <450 | <800 |
| | GSU | <500 | <650 | <1000 |
| $V_1$ – Dubious | GRID | ≥350….<450 | ≥450…<800 | ≥800…..<1600 |
| | GSU | ≥500….<650 | ≥650….<1000 | ≥1000….<1600 |
| $V_2$ – Faulty | GRID | ≥450….<800 | ≥800….<1600 | ≥1600…..<3000 |
| | GSU | ≥650….<1000 | ≥1000…<1600 | ≥1600…..<3000 |
| $V_3$ – Dangerous | GRID | ≥800 | ≥1600 | ≥3000 |
| | GSU | ≥1000 | ≥1600 | ≥3000 |

### 4.4 The Duval Triangle method

The Duval Triangle method; another DGA diagnostic method for oil insulated equipment (mainly transformer) developed by Michael Duval [4] in 1974.In this method concentration (ppm) of methane ($CH_4$), ethylene ($C_2H_4$), and acetylene ($C_2H_2$) are expressed as percentages of the total ($CH_4$ + $C_2H_4$ + $C_2H_2$) and plotted as a point (%$CH_4$, %$C_2H_4$, %$C_2H_2$) in a triangular coordinate system on a triangular chart which has been subdivided into fault zones. The fault zone in which the point is located designates the likely fault type which produced that combination of gas concentrations.

The Duval Triangle method, like any other DGA diagnostic method, should be applied only when there is some suspicion of a fault, based on an increase in combustible gas or some other suspicious symptom. The diagnostic method itself is not a means of fault detection. Because of the relative inaccuracy of gas-in-oil concentration measurements at low concentrations, DGA diagnostic methods, including the Duval Triangle, should not be applied unless the gas concentrations are well above the detection limit.

The faults which are detected by Duval triangle are expressed as follows;

- Partial Discharge (PD)
- Discharges of Low energy (D1)
- Discharges of High energy (D2)
- Thermal fault, $\mathrm{T} < 300\ ℃$ (T1)
- Thermal fault, $300 < \mathrm{T} < 700\ ℃$ (T2)
- Thermal fault, $\mathrm{T} > 700\ ℃$ (T3)
- Thermal & Electrical fault (DT)

### *4.4.1 A procedure to use the Duval triangle*

Graphical use of Duval triangle is very simple. Consider the three side of triangle in triangular coordinates (x, y and z) representing the relative proportion of $CH_4$, $C_2H_4$ and $C_2H_2$, from 0-100% for each gas.

There are two different procedures to use this Novel method:

- By using total accumulated gas
- By using total increase between conjugative samples

For this Duval Triangle representation at first concentration of these three gases or recent increase in concentration of these gases is to be found out. After finding out the concentration calculation of the percentage of each gas is needed. Three sides of the triangle represent percentage of three gases. After calculating the percentage each gas, lines of $CH_4$ % quantity parallel to $C_2H_2$ line, $C_2H_4$% quantity parallel to $CH_4$ line and $C_2H_2$% quantity parallel to $CH_4$ are to be drawn. Thus, drawn intersection of all three lines would indicate the fault for the gas;

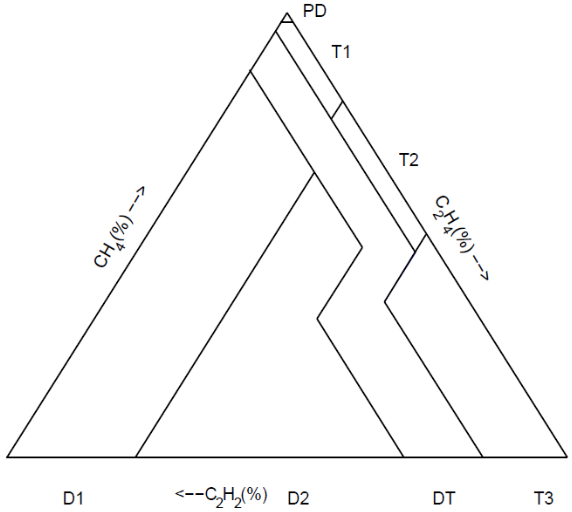



Figure 4.1: A classical Duval triangle

Example-1: Suppose that a transformer is found to have recent increases of 45 ppm of $CH_4$, 90 ppm of $C_2H_4$ and 15 ppm of $C_2H_2$. Hence;

% $CH_4$ = (45/150)*100 = 30 %

% $C_2H_4$ = (90/150)*100 = 60 %

% $CH_4$ = (15/150)*100 = 10 %

Plotting these values in Duval triangle;

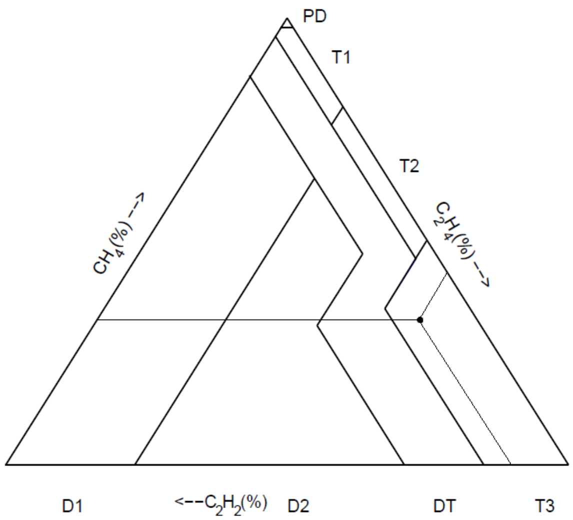



Figure 4.2: Graphical analysis on Duval triangle

The point representing our gas data falls in the T3 fault zone, indicating a high-temperature thermal fault ($T_3$) i.e.$T > 700$ ℃, which is typically a "hot metal" fault.

### 4.4.2 *Software implementation of Duval triangle*

For the software implementation the Duval triangle, the polygons for the zones of seven key faults were generated using the following coordinates in terms of percentages of $CH_4$, $C_2H_4$ and $C_2H_2$, from 0% to 100% respectively.

**Table 4.4:** Triangular coordinates for Duval triangle zones [12]

| Area | Points | $CH_4$ (%) | $C_2H_4$ (%) | $C_2H_2$ (%) |
|---|---|---|---|---|
| PD | PD1 | 98 | 2 | 00 |
| | PD2 | 100 | 00 | 00 |
| | PD3 | 98 | 00 | 2 |
| D1 | D11 | 0 | 0 | 100 |
| | D12 | 0 | 23 | 77 |
| | D13 | 64 | 23 | 13 |
| | D14 | 87 | 00 | 13 |
| D2 | D21 | 00 | 23 | 77 |
| | D22 | 0 | 71 | 29 |
| | D23 | 31 | 40 | 29 |
| | D24 | 47 | 40 | 13 |
| | D25 | 64 | 23 | 13 |
| DT | DT1 | 00 | 71 | 29 |
| | DT2 | 00 | 85 | 15 |
| | DT3 | 35 | 50 | 15 |
| | DT4 | 46 | 50 | 4 |
| | DT5 | 96 | 00 | 4 |
| | DT6 | 87 | 00 | 13 |
| | DT7 | 47 | 40 | 13 |
| | DT8 | 31 | 40 | 29 |
| T1 | T11 | 76 | 20 | 4 |
| | T12 | 80 | 20 | 00 |
| | T13 | 98 | 2 | 00 |
| | T14 | 98 | 00 | 2 |
| | T15 | 96 | 00 | 4 |
| T2 | T21 | 46 | 50 | 4 |
| | T22 | 50 | 50 | 00 |
| | T23 | 80 | 20 | 00 |
| | T24 | 76 | 20 | 4 |
| T3 | T31 | 00 | 85 | 15 |
| | T32 | 00 | 100 | 00 |
| | T33 | 50 | 50 | 00 |
| | T34 | 35 | 50 | 15 |

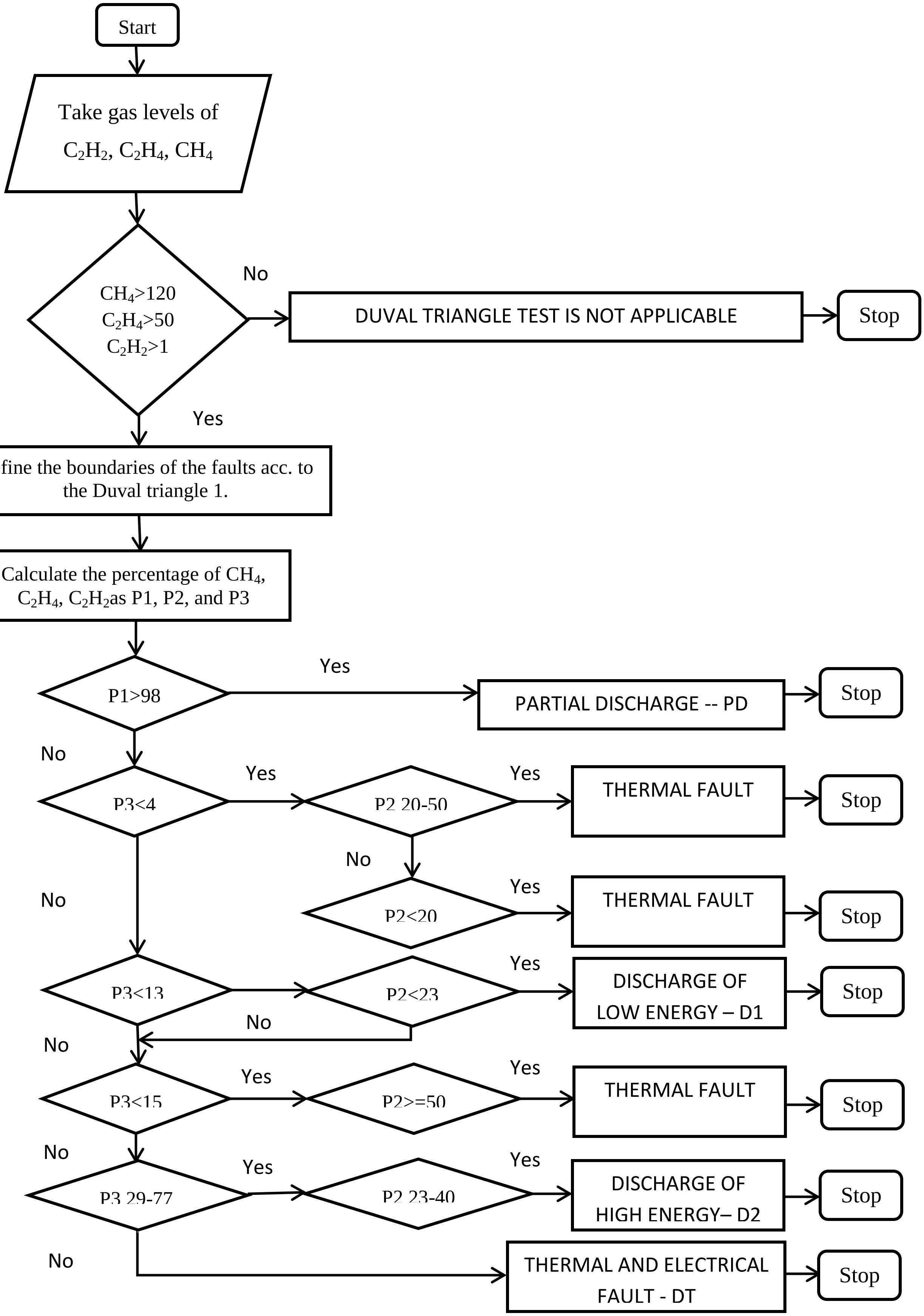



Figure 4.3: A flow chart for Duval triangle [13]

A flow-chart for software development of Duval triangle on MATLAB is developed and shown in Figure 4.3. To define each polygon, the defined points are converted to Cartesian coordinates for percentage of gases for type of fault.

If percentages of any two gases are known, the percentage of another gas can be found out easily by simple mathematical calculation. For MATLAB programming at first the coordinates of different regions are to be shown as in the Table 4.4.

From the Figure 4.4, *x* and *y* coordinates are to be calculated doing analysis trigonometrically.

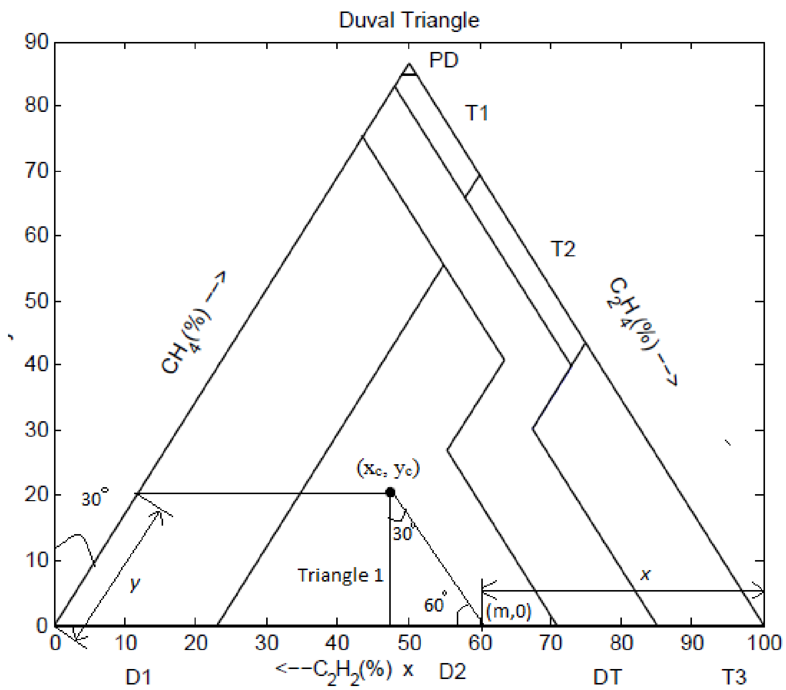



Figure 4.4: Duval Triangle for finding *x* and *y* coordinates

If the percentage value of $CH_4$ is '*y*' then *y* coordinate will be $y_c = y\cos(30°)$…… (*i*)

If the percentage value of $C_2H_2$ is '*x*' then *x* coordinate will be;

$$\tan(60°) = y_c/(m - x_c);$$

$$=> x_c = m - y_c \cot(60°);$$

$$=> x_c = 100 - x - y_c \cot(60°);$$

$$=> x_c = 100 - x - y\cos(30°)\cot(60°)\text{…… }(ii)$$

Hence these two equations may be summarized as;

*x* coordinates;

$$x_c = 100 - (\%\ value\ of\ C_2H_2) - (\%\ value\ of\ CH_4) * \cos(30°) * \cot(60°)$$

& y coordinates;

$$y_c = (\%\ value\ of\ CH_4) * \cos(30°)$$

From this equation it is clear that with the value of percentage of concentration of $CH_4$ and $C_2H_2$, it is sufficient to estimate the fault. But for ppm level concentration values of all three gases are required.

Using these above equations (*i*) & (*ii*) and by the help of MATLAB the fault region of the transformer can be estimated. Taking the same values as in Example-1: Suppose that a transformer is found to have recent increases of 45 ppm of $CH_4$, 90 ppm of $C_2H_4$ and 15 ppm of $C_2H_2$. Then putting these values in the program the founded result or the Duval triangle is shown in Figure 4.5.

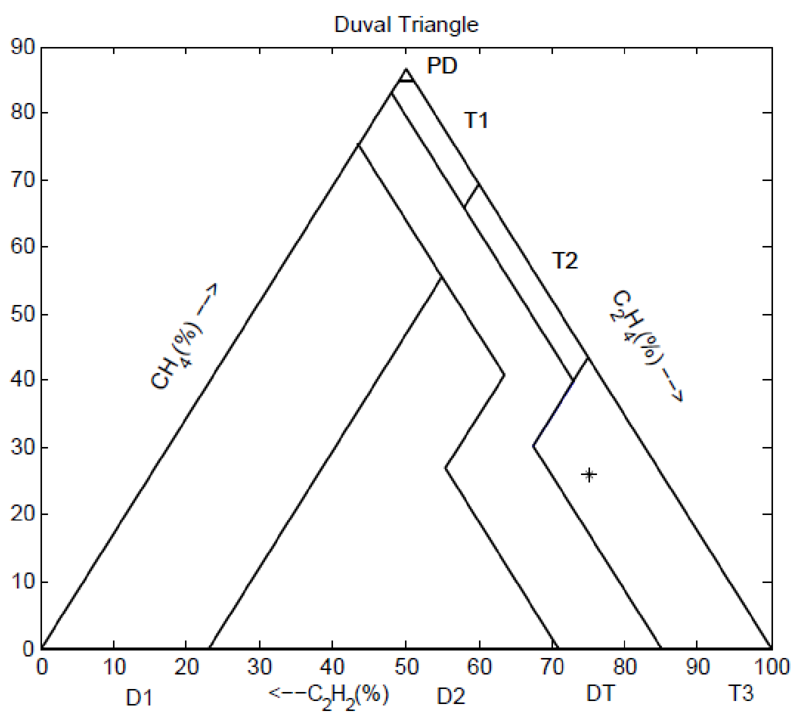



Figure 4.5: Software analysis of Duval Triangle

The point representing our gas data falls in the T3 fault zone, indicating a high-temperature thermal fault (T3) i.e.$T > 700$ ℃, which is typically a "hot metal" fault. That means the fault is Extensive formation of carbon particles in oil, metal coloration (800 °C) or metal fusion (>1000 °C).

Hence from the above analyses it is clear that graphical, flow chart and the software analysis gives the same result. So this method has satisfied the fault diagnosis.

# CHAPTER 5

# NOVEL METHODS FOR DETECTION OF DISSOLVED GASES

## 5.1 Introduction

As discussed earlier the accurate knowledge of the condition of transformers is essential for all electrical networks. With the help of this information the maximized and expensive failures can be avoided. As transformer is oil filled equipment the DGA should give accurate, rapid and reliable results in the field. So new technologies have been achieved to get extremely high performance standards and genuine portability, giving measurement of all the fault gases plus moisture. Infrared photo-acoustic spectroscopy (PAS) is such kind of the methods in which the gases are extracted from the oil sample using highly stable proprietary dynamic headspace equilibrium and then measured.

## 5.2 Infrared Photo-Acoustic Spectroscopy for DGA

The conceptual design of a practical PAS measurement module is shown in Figure. A simple hot wire source produces broadband radiation across the IR range that is focused into the measurement cell using a parabolic mirror. When a species absorbs some of the incoming light, one of several mechanisms of de-excitation is intermolecular colliding, which ultimately leads to increases in translation energy of the gas particles — that is, heating. According to the various gas laws, an increase in the temperature of the gas leads to an increase in the pressure of an isochoric (constant- volume) sample. The chopper wheel rotates at a constant speed to give a modulated frequency light signal from single to several thousand hertz [15].

Before reaching the measurement cell the radiation is passed through one of a number of optical filters. These filters are designed to transmit the specific wavelengths chosen to excite one of the compounds under investigation.

The sample is introduced into the measurement cell and the acoustic signal level is recorded at the chopper frequency from the microphones as each optical filter is indexed into the light path. Incoming light of varying wavelength will change the amount of light absorbed, the amount of pressure changes occurring and hence the amount of sound or the acoustic signal produced.

The series of readings produced then gives the concentration of the desired compounds in the sample.

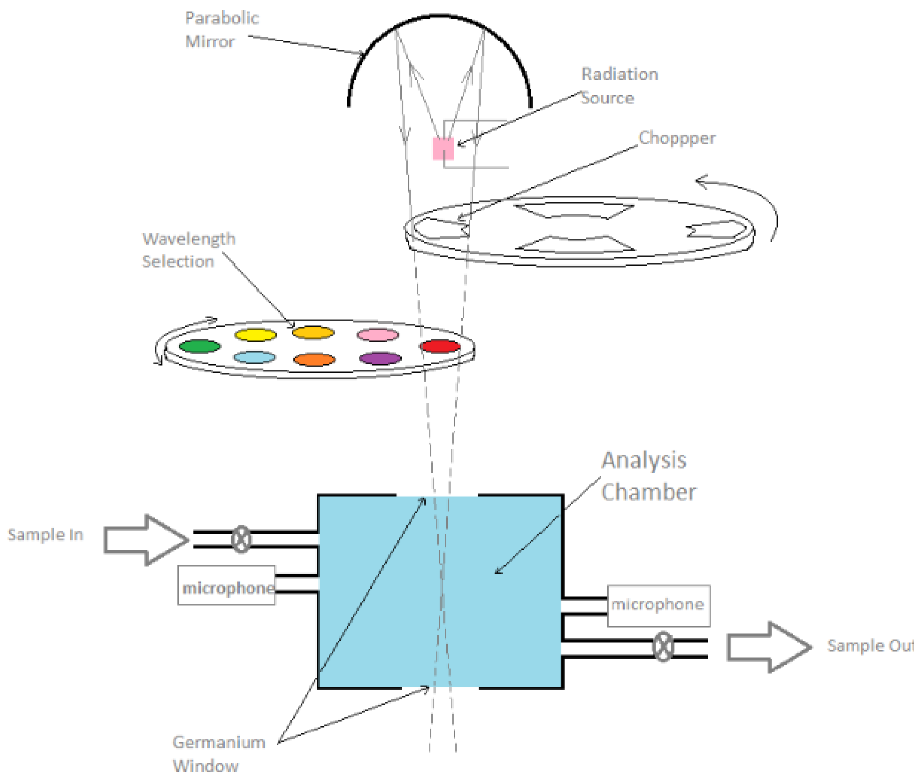



Figure 5.1: Photo-Acoustic Spectrometer Concept

## 5.3 TRANSPORT X

The Kelman TRANSPORT X is a compact portable Dissolved Gas Analysis (DGA) system which analyses oil samples for all dissolved fault gases and moisture using infrared photo-acoustic spectroscopy. If abnormal levels are detected, it further provides a diagnostic using various IEEE/IEC approved interpretation rules.

The TRANSPORT X can also test direct gas samples taken from transformer headspace or a Buchholz Relay. The dynamic range of measurement and ability to have no contamination between samples means it very suitable for testing tap-changers and circuit breakers also.

The TRANSPORT X is contained within a rugged, impact resistant, carrying case. The accessories include sample bottle with connections and pipes and a syringe for extracting oil sample from the equipment and injecting it into the bottle. It contains an embedded PC and touch screen which makes it very much user friendly. A thermal printer is also provided to take the hard copy of the records.

A portable infrared photo-acoustic spectroscopy based DGA system TRANSPORT X and its schematic diagram of operation are shown in the figure below.

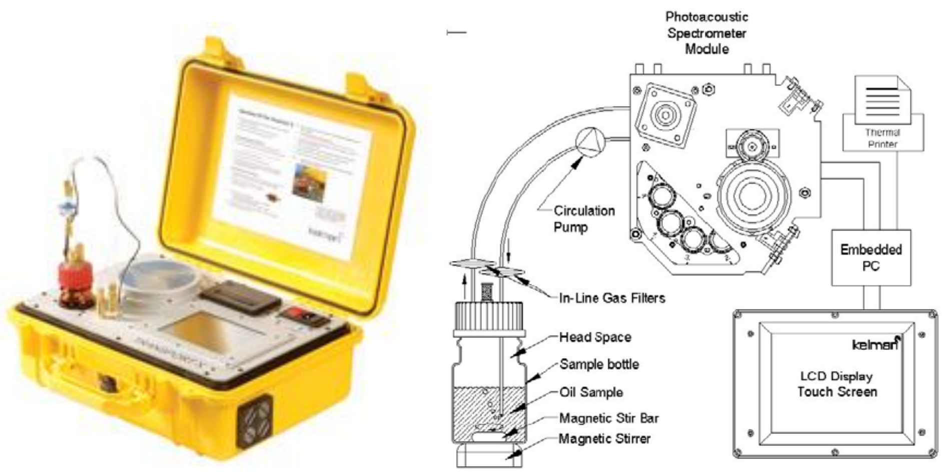



Figure 5.2: Details of TRANSPORT X

Extensive field and laboratory use worldwide has proven that the TRANSPORT X test gives highly reliable results and that it is genuinely suitable for field conditions. It has Wide detection range with excellent accuracy for all seven fault gases (typically 1-50,000 ppm). It also allows hot oil samples to be cooled for testing in minutes.

# CHAPTER 6

# EXTENSION TO THE DUVAL TRIANGLE

The Duval triangle method previously discussed was the classical Duval Triangle method for Transformers, Bushings and cables filled with mineral oils. There are other triangles analysed by Michael Duval, which are for Bio temperature oil, FR#3 oil and silicon oil etc. For mineral oil he has also analysed low temperature faults & faults in paper in mineral oils and Thermal faults & faults in paper in mineral oils [16].

While the previous method was giving the results with the value of the concentration of methane, ethylene and acetylene; these analysis give us more accurate information about the transformer taking the concentration of other gases like hydrogen and ethane into consideration.

It is an extension to the classical Duval triangle which gives more specific information about the fault which is helpful for the accurate analysis.

There are two such methods which are helpful to give more details about the faults in a transformer, such as;

- Duval Triangle for low temperature faults & faults in paper in mineral oils
- Duval Triangle for Thermal faults & faults in paper in mineral oils

Duval Triangle for low temperature faults includes hydrogen, methane and ethane for fault analysis while the Duval Triangle for Thermal faults includes methane, ethylene and ethane for the fault analysis.

## 6.1 Duval Triangle for low temperature faults & faults in paper in mineral oils

This Duval triangle for low temperature faults in mineral oils uses three gases for the analysis such as hydrogen, methane and ethane. It is used to get more information about the faults identified as low temperature faults i.e. PD, $T_1$ and $T_2$ as in classical Duval Triangle. It should not be used for $D_1$, $D_2$ and $T_3$ as these are high temperature thermal faults but this triangle is only helpful for low temperature faults.

There are five zones in this Duval triangle such as;

- PD- Corona partial discharge
- S- Stray gassing of mineral oil ( T < 200$^{o}$ C )
- C- Hot-spots with carbonization of paper
- O- Over-heating
- N/D- Not determined

In zone C, the probability of having carbonization of paper is 80 %.

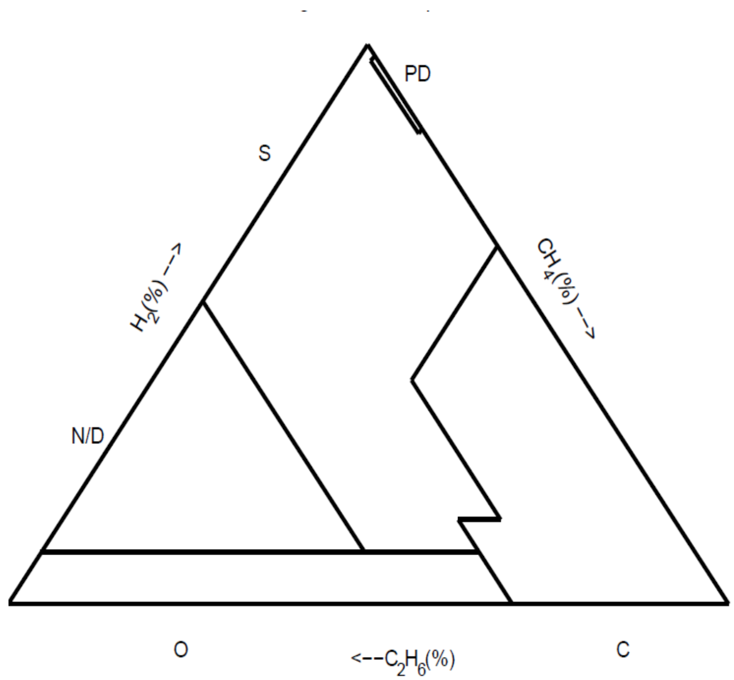



Figure 6.1: Duval Triangle for low temperature faults

### *6.1.1 Software Implementation*

In software implementation of Duval triangle it is first required to find out the coordinates of each zone and then it is applied in MATLAB as in the case of classical Duval triangle for getting out the incipient fault.

If the point lies in N/D region then the result found out from the Classical Duval Triangle will be taken as the final fault for that particular Dissolved gas analysis.

The coordinates of the different zones of the triangle are given below in the Table 6.1;

**Table 6.1:** Triangular coordinates of Duval triangle for low temperature fault

| Area | Points | $H_2$ (%) | $CH_4$ (%) | $C_2H_6$ (%) |
|---|---|---|---|---|
| PD | PD1 | 98 | 2 | 00 |
| | PD2 | 97 | 2 | 1 |
| | PD3 | 84 | 15 | 1 |
| | PD4 | 85 | 15 | 00 |
| O | O1 | 00 | 00 | 100 |
| | O2 | 00 | 70 | 30 |
| | O3 | 9 | 61 | 30 |
| | O4 | 9 | 00 | 91 |
| N/D | N/D 1 | 9 | 00 | 91 |
| | N/D 2 | 9 | 44 | 46 |
| | N/D 3 | 54 | 00 | 46 |
| S | S1 | 9 | 44 | 46 |
| | S2 | 9 | 61 | 30 |
| | S3 | 15 | 55 | 30 |
| | S4 | 15 | 61 | 24 |
| | S5 | 40 | 36 | 24 |
| | S6 | 64 | 36 | 00 |
| | S7 | 85 | 15 | 00 |
| | S8 | 84 | 15 | 1 |
| | S9 | 97 | 2 | 1 |
| | S10 | 98 | 2 | 00 |
| | S11 | 100 | 00 | 00 |
| | S12 | 54 | 00 | 46 |
| C | C1 | 00 | 70 | 30 |
| | C2 | 00 | 00 | 100 |
| | C3 | 64 | 36 | 00 |
| | C4 | 40 | 36 | 24 |
| | C5 | 15 | 61 | 24 |
| | C6 | 15 | 55 | 30 |

## 6.2 Duval Triangle for Thermal faults & faults in paper in mineral oils

This Duval Triangle method is used for Thermal faults in mineral oils. It uses three gases for the analysis such as methane, ethylene and ethane. It is used to get more information about the faults identified as Thermal faults i.e. $T_2$ and $T_3$ in classical Duval triangle. It should not also be used for faults like $D_1$, $D_2$.

There are seven zones in this Duval triangle such as;

- PD- Corona partial discharge
- S- Stray gassing of mineral oils ( $T<200^oC$ )

- C-Hot-spot with carbonization of paper
- O- Over-heating( $T<250^{o}C$ )
- $T_2$- Thermal faults of higher temperature ( $300^{o}C< T <700^{o}C$ )
- $T_3$- Thermal faults of very high temperature ( $T >700^{o}C$ )
- N/D- Not determined

In zone C, the probability of having carbonization of paper is 90 %.

If the above two triangles do not agree it means that the fault may be a mixture of faults.

Like the Duval Triangle for low temperature fault the triangle below is used for getting more information about the Thermal faults. The different zones are also shown in the triangle. If the point lies in N/D zone it means that this triangle won't give more information about the thermal fault.

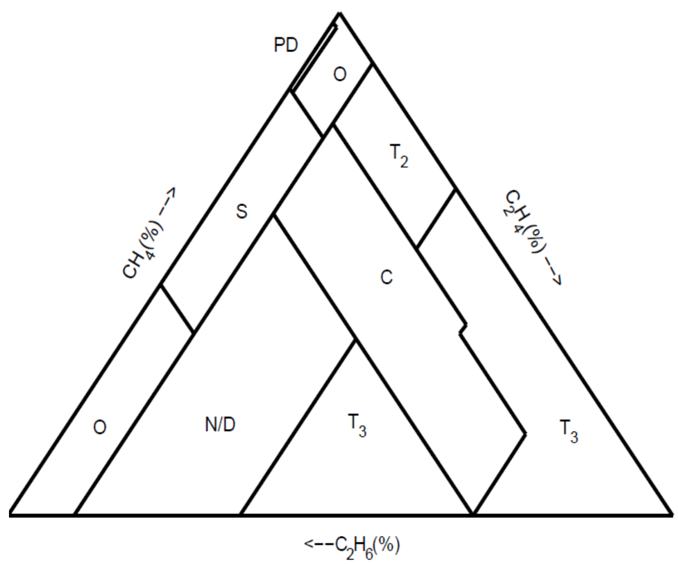



Figure6.2: Duval Triangle for Thermal faults

### 6.2.1 *Software Implementation*

For each zone coordinates of the vertices are found out.

The coordinates of the different zones of the triangle are given below in the Table 6.2.

Using these coordinates the incipient fault inside the transformer can be estimated. For the practical analysis sample from different transformers is to be collected and to perform the gas analysis to get the concentration of each gases. Putting these values in the software the fault can be estimated.

**Table 6.2:** Triangular coordinates of Duval triangle for Thermal fault

| Area | Points | $CH_4$ (%) | $C_2H_4$ (%) | $C_2H_6$ (%) |
|---|---|---|---|---|
| PD | PD1 | 85 | 00 | 15 |
| | PD2 | 84 | 1 | 15 |
| | PD3 | 97 | 1 | 2 |
| | PD4 | 98 | 00 | 2 |
| S | S1 | 46 | 00 | 54 |
| | S2 | 36 | 10 | 54 |
| | S3 | 75 | 10 | 15 |
| | S4 | 85 | 00 | 15 |
| N/D | N/D 1 | 00 | 00 | 100 |
| | N/D 2 | 0 | 35 | 65 |
| | N/D 3 | 35 | 35 | 30 |
| | N/D 4 | 60 | 10 | 30 |
| S | O1 | 00 | 00 | 100 |
| | O2 | 00 | 10 | 90 |
| | O3 | 36 | 10 | 54 |
| | O4 | 46 | 00 | 54 |
| | O5 | 84 | 1 | 15 |
| | O6 | 75 | 10 | 15 |
| | O7 | 90 | 10 | 00 |
| | O8 | 100 | 00 | 00 |
| | O9 | 98 | 00 | 2 |
| C | C1 | 00 | 70 | 30 |
| | C2 | 16 | 70 | 14 |
| | C3 | 36 | 50 | 14 |
| | C4 | 38 | 50 | 12 |
| | C5 | 78 | 10 | 12 |
| | C6 | 00 | 35 | 65 |
| T2 | T21 | 53 | 35 | 12 |
| | T22 | 65 | 35 | 00 |
| | T23 | 90 | 10 | 00 |
| | T24 | 70 | 10 | 12 |
| T3 | T31 | 0 | 35 | 65 |
| | T32 | 0 | 70 | 30 |
| | T33 | 35 | 35 | 30 |
| | T34 | 00 | 100 | 00 |
| | T35 | 65 | 35 | 00 |
| | T36 | 53 | 35 | 12 |
| | T37 | 38 | ‘50 | 12 |
| | T38 | 36 | 50 | 14 |
| | T39 | 16 | 70 | 16 |

# CHAPTER 7

## SOFTWARE ANALYSIS AND PRACTICAL DATA

The concentrations of each gas of three collected samples are given below;

**Table 7.1:** Concentration of each gas of three collected samples

| Samples | Key gases | 2010 | 2011 | 2012 | 2013 |
|---|---|---|---|---|---|
| MSDS2/Transformer#2 | Hydrogen | <5 | <5 | 15 | 17 |
| | Water | 81 | 19 | 24 | 57 |
| | Carbon Dioxide | 1288 | 2002 | 1261 | 1386 |
| | Carbon monoxide | 61 | 247 | 133 | 133 |
| | Ethylene | 12 | 9 | 7 | 8 |
| | Ethane | 17 | 5 | 5 | 3 |
| | Methane | 3 | 9 | 5 | 12 |
| | Acetylene | <0.5 | <0.5 | 14.5 | 25.5 |
| | TDCG | | 275 | 179 | 199 |
| CRM Transformer#53 | Hydrogen | 35 | <5 | 35 | 26 |
| | Water | 89 | 42 | 53 | 75 |
| | Carbon Dioxide | 7616 | 1181 | 8553 | 7982 |
| | Carbon monoxide | 640 | 40 | 663 | 552 |
| | Ethylene | 60 | 5 | 43 | 34 |
| | Ethane | 89 | 3 | 46 | 33 |
| | Methane | 77 | 7 | 51 | 39 |
| | Acetylene | <0.5 | <0.5 | <0.5 | <0.5 |
| | TDCG | 901 | 57 | 836 | 585 |
| Tandem mill rectifier transformer#4 | Hydrogen | <5 | <5 | <5 | <5 |
| | Water | 72 | 36 | 38 | 56 |
| | Carbon Dioxide | 7013 | 4257 | 5520 | 5925 |
| | Carbon monoxide | 469 | 319 | 577 | 420 |
| | Ethylene | 25 | 13 | 17 | 37 |
| | Ethane | 18 | 8 | 9 | 12 |
| | Methane | 9 | 6 | 7 | 8 |
| | Acetylene | 0.5 | <0.5 | <0.5 | <0.5 |
| | TDCG | 524 | 348 | 514 | 482 |

Here MATLAB programs have been designed which shows the incipient fault occurred in the transformer by Ratios method and Duval triangle method. After getting the results comparison with the practical results is to be done.

## 7.1 Analysis of oil of CRM, Transformer # 53

DGA analysis result of CRM, Transformer # 53 is taken;

The practical results of concentration of different gases are;

kelman

Kelman Ltd TRANSPORT X

DGA Results

Type:
Transformer
Equipment ID:
TR #53
Location:
CRM
Manufacturer:
......
Sampling Pt:
..
Sample Source:
Oil Sample
Date:
09 Jan 13 14:52 PM

| | | |
|---|---|---|
| Hydrogen | H2: | 26 |
| Water | H2O: | 75 |
| CarbonDioxide | CO2: | 7982 |
| CarbonMonoxide | CO: | 552 |
| Ethylene | C2H4: | 34 |
| Ethane | C2H6: | 33 |
| Methane | CH4: | 39 |
| Acetylene | C2H2: | <0.5 |
| TDCG | : | 685 |

Caution: sample problem
(See TRANSPORT X for
more information)
High water content

Figure 7.1: Output of TRANSPORT X for CRM, Transformer # 53

In the interface of Transport X the result is;

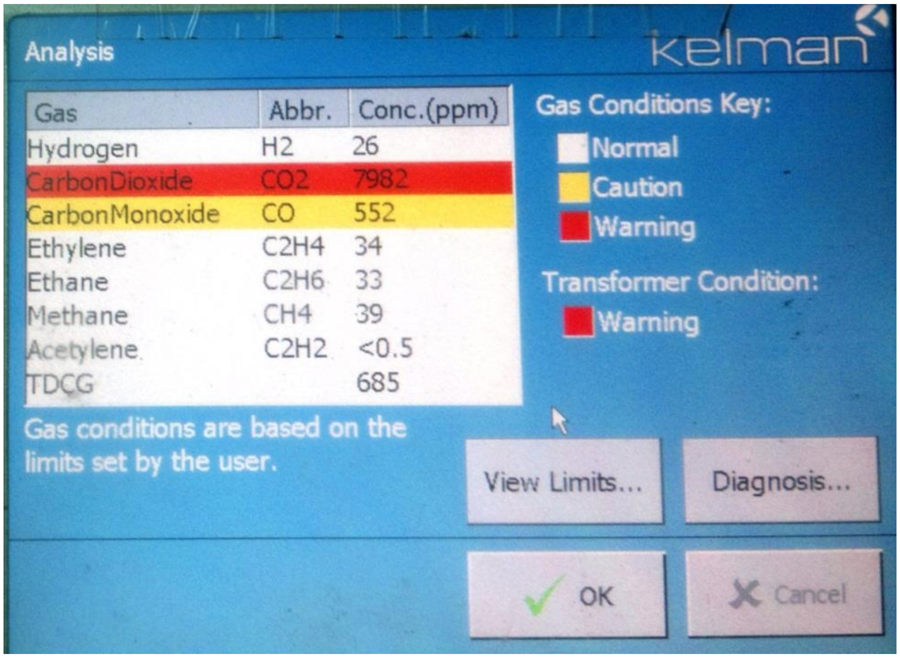
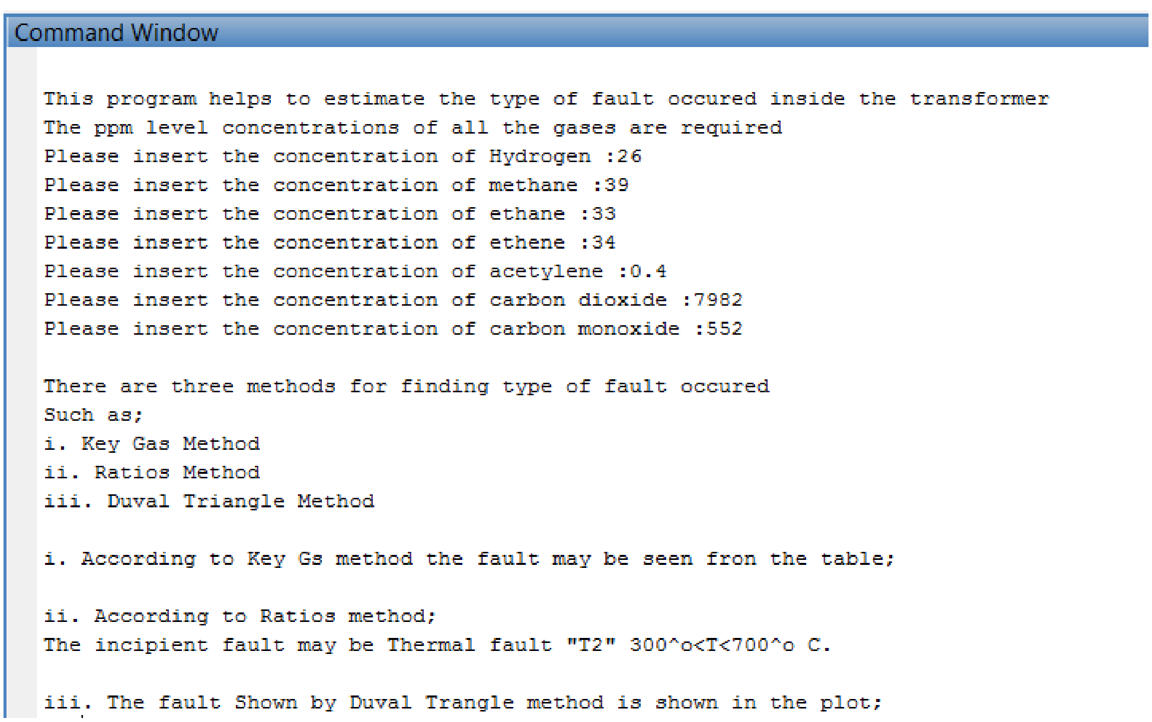



Figure 7.2: Interface of TRANSPORT X for CRM, Transformer # 53

Putting these results in the software the conclusion was found out to be;



```
Command Window

This program helps to estimate the type of fault occured inside the transformer
The ppm level concentrations of all the gases are required
Please insert the concentration of Hydrogen :26
Please insert the concentration of methane :39
Please insert the concentration of ethane :33
Please insert the concentration of ethene :34
Please insert the concentration of acetylene :0.4
Please insert the concentration of carbon dioxide :7982
Please insert the concentration of carbon monoxide :552

There are three methods for finding type of fault occured
Such as;
i. Key Gas Method
ii. Ratios Method
iii. Duval Triangle Method

i. According to Key Gs method the fault may be seen fron the table;

ii. According to Ratios method;
The incipient fault may be Thermal fault "T2" 300^o<T<700^o C.

iii. The fault Shown by Duval Trangle method is shown in the plot;
```

Figure 7.3: Software analysis of given concentrations for CRM, Transformer # 53

From the software according to Ratios method the result is found out as $T_2$ i.e. Thermal fault $300^o$ c < T < $700^o$ C. Comparing this result with the ratios method analysis in the practical instrument as shown below;

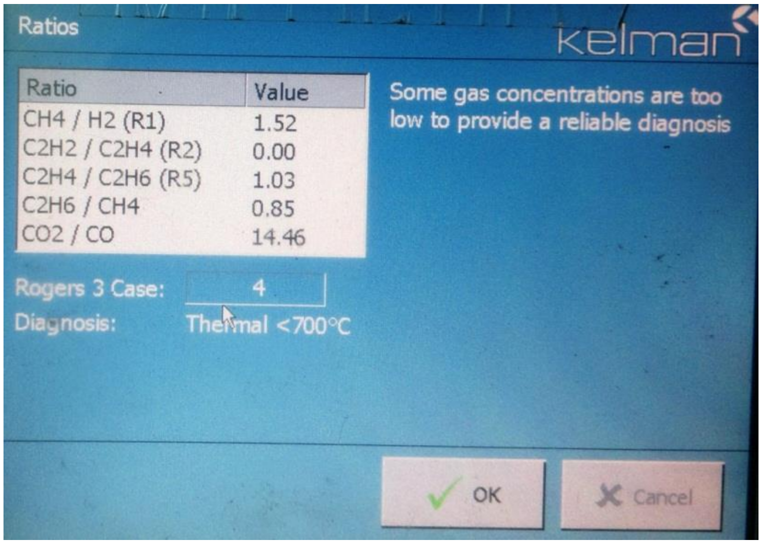



Figure 7.4: Ratio's method in interface of TRANSPORT X for CRM, Transformer # 53

Hence By comparing, the same result was found out.

Again from the software part the Duval triangle has the point as follows;

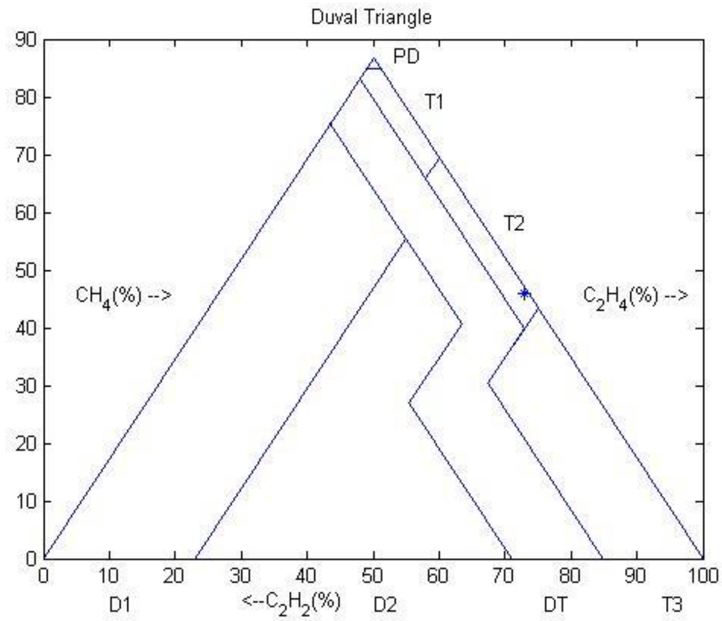



Figure 7.5: Duval Triangle output of the given concentrations for CRM, Transformer # 53

Duval Triangle from the software analysis part also gives the same $T_2$ fault. Comparing it with the practical results as shown below;

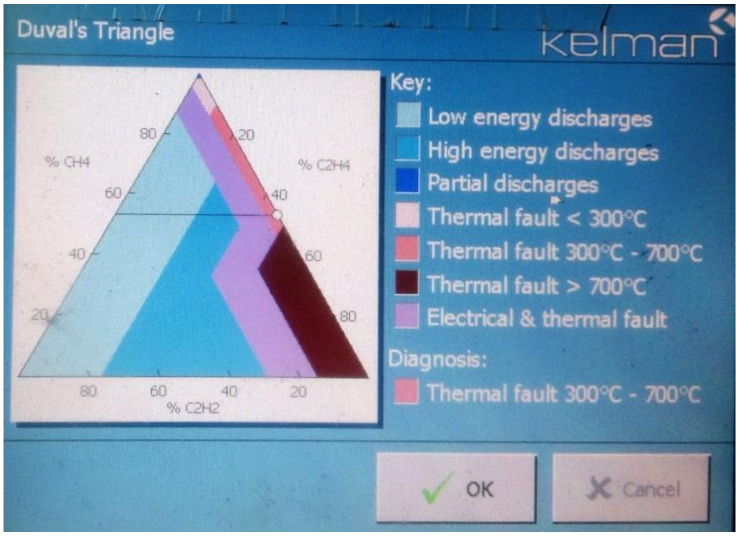



Figure 7.6: Duval Triangle output of the interface of TRANSPORT X

Hence all the Diagnosis methods give the same result. Hence the fault may be $T_2$ i.e. Thermal fault $300^o$ C < T < $700^o$ C.

It shows that the incipient fault of the transformer may be $T_2$. So further putting these values in extension of Duval triangle below the point was found out in the region ‘S’. Hence the fault may be Stray gassing of mineral oil (T < $200^o$ C).

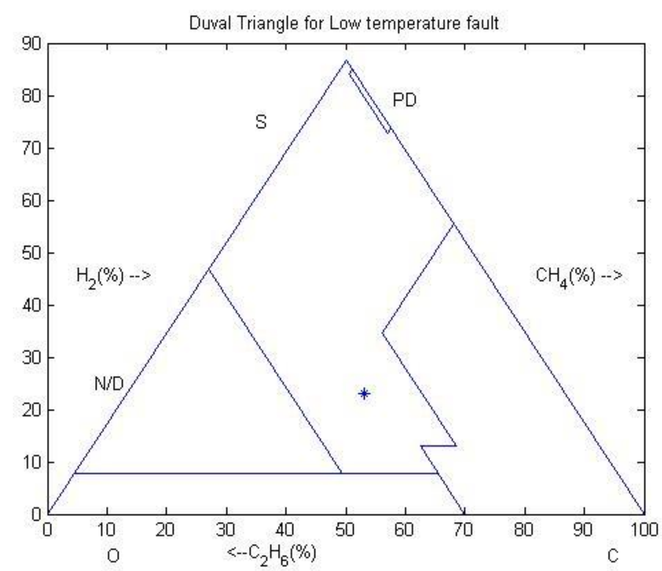



Figure 7.7: Duval Triangle for low temperature fault output of the MATLAB

## 7.2 Analysis of oil of Tandem mill rectifier transformer#4

Now for DGA analysis sample result of Tandem mill rectifier transformer#4 was taken;

The concentration of different gases shown from the interface of the TRANSPORT X below;

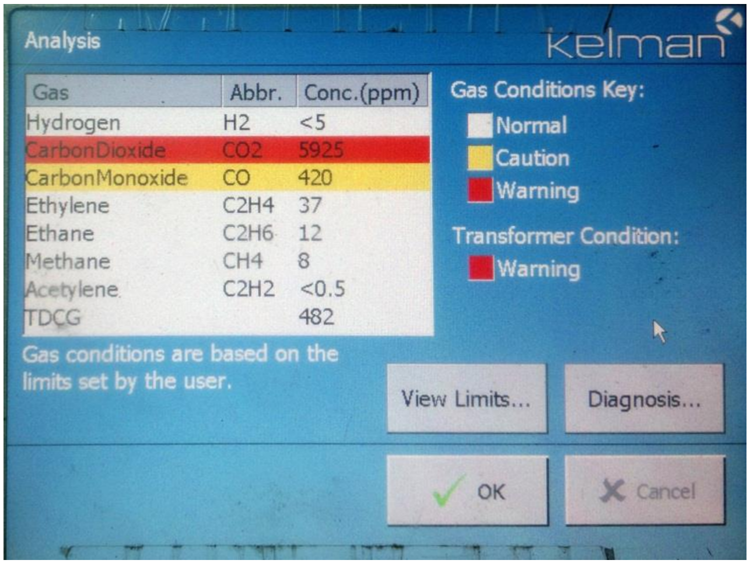



Figure 7.8: Interface of TRANSPORT X for Tandem mill rectifier transformer#4

Putting these results in the software the conclusion was found out to be;

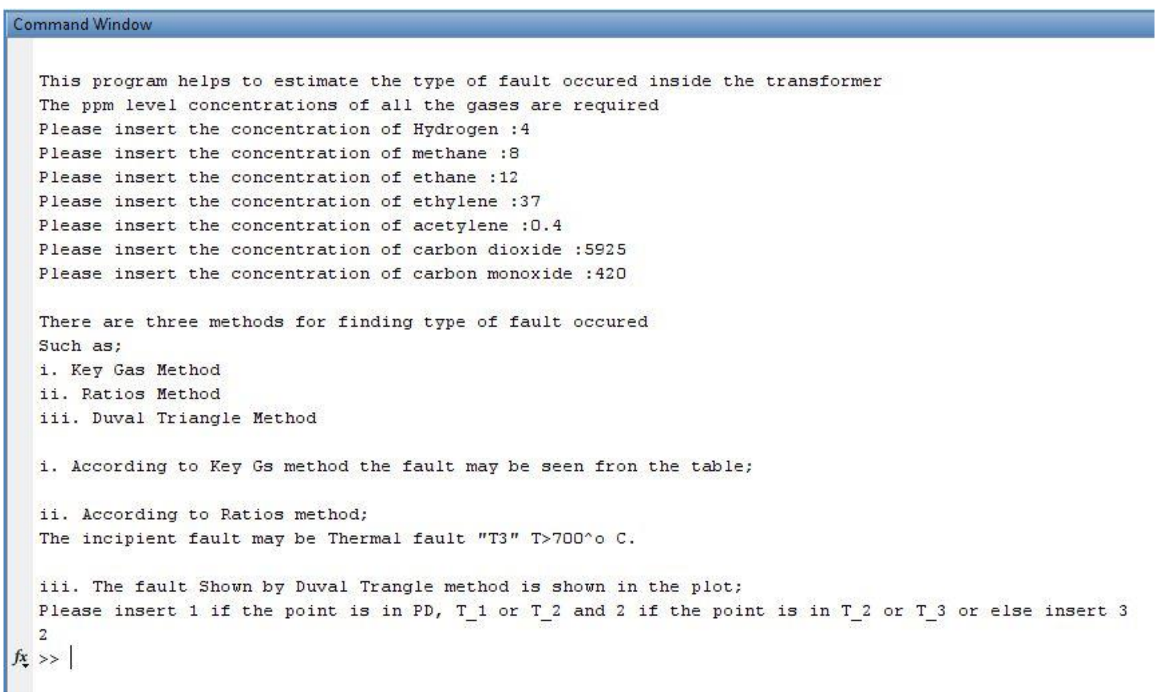



Figure 7.9: Software analysis of given concentrations for TM rectifier transformer#4

From the software according to Ratios method the result is found out as $T_3$ i.e. for Thermal fault $T > 700^o$ C. Comparing this result with the ratios method analysis in the practical instrument as shown below;

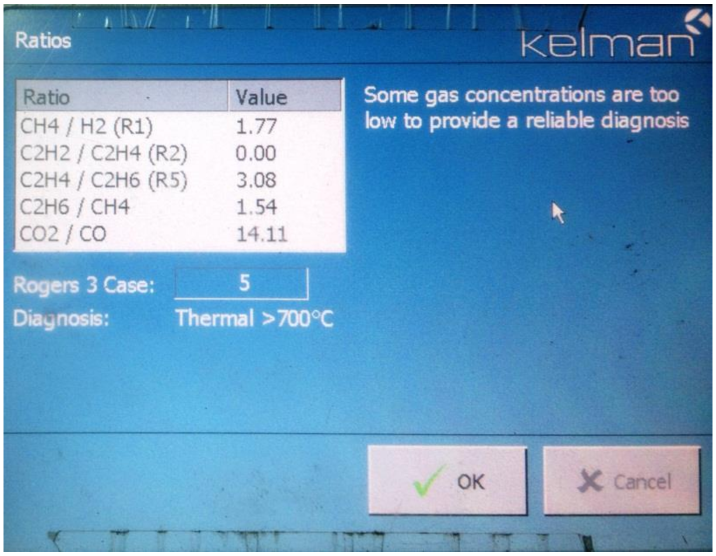



Figure 7.10: Ratio's method in interface of TRANSPORT X for TM rectifier transformer#4

Hence By comparing, the same result was found out.

Again from the software part the Duval triangle has the point as follows;

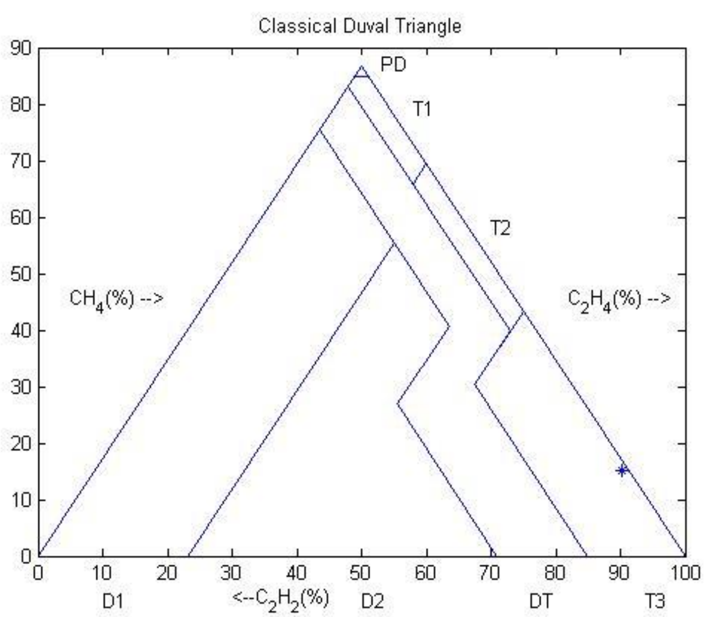



Figure 7.11: Duval Triangle output of the given concentrations for TM rectifier transformer#4

Duval Triangle from the software analysis part also gives the same $T_3$ fault. Comparing it with the practical results as shown below;

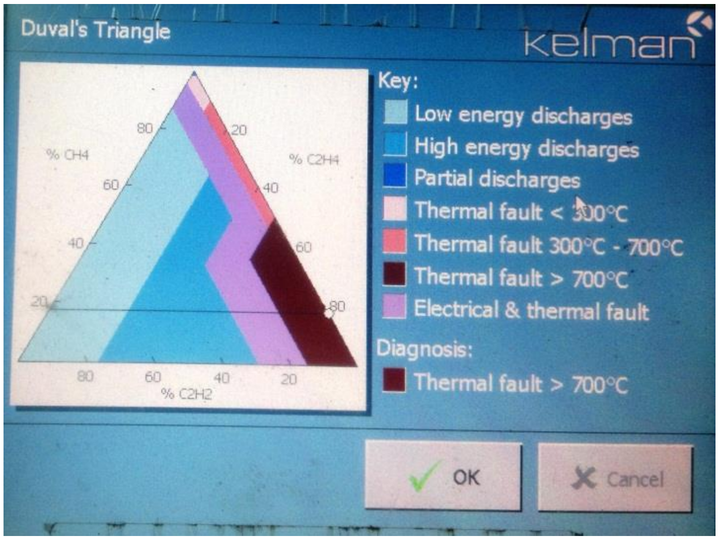



Figure 7.12: Duval Triangle output of the interface of TRANSPORT X

Hence all the Diagnosis methods give the same result. Hence the fault may be $T_3$ i.e. Thermal fault T > 700$^{o}$ C.

It shows that the incipient fault of the transformer may be $T_3$. So further putting these values in extension of Duval triangle below the point was found out in the region 'C'. Hence the fault may be Hot-spot with carbonization of paper. So extension to the Duval triangle gives more appropriate result.

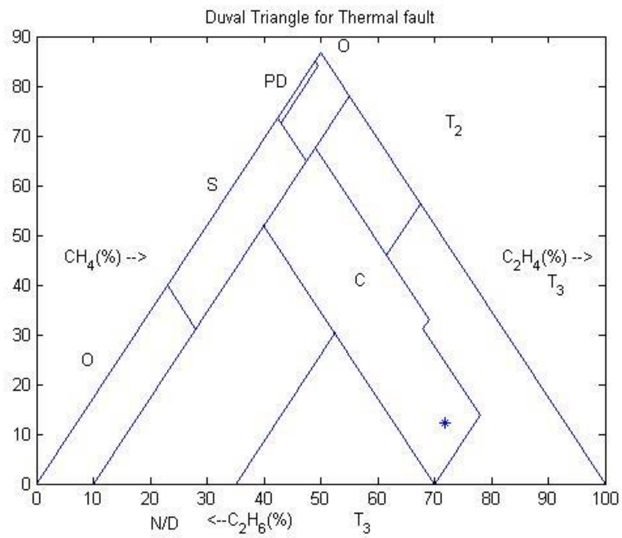



Figure 7.13: Duval Triangle for Thermal fault output of the MATLAB

# CHAPTER 8

## CONCLUSIONS AND FUTURE WORKS

Dissolved gas analysis (DGA) is a chemical rather than an electrical method. The cost of each DGA is relatively inexpensive. All these factors make DGA a powerful tool in the preventive maintenance of transformers.

The calculation considers not only typical test results but also other parameters such as physical observations, tap changer, bushing condition, oil condition, load history, maintenance work orders, age and trends of transformer failure etc.

The technology presently exists and is being used to detect and determine fault gases below the part per million levels. However there is still much scope for improvement in the technology especially in developing the methods of interpreting the results and correlating them with incipient faults. It is also important to realize that even though there is further need for improvement in the technique, the analysis of dissolved fault gases represents a practical and effective method for the detection of incipient faults inside the transformer and the determination of their severity. In addition to utility companies, many other industries and installations that have on-site transformers are realising that the technique of dissolved fault gas analysis is an extremely useful in condition monitoring, if not essential, part of a well-developed preventative maintenance program for power transformers.

Duval triangle interpretation is a robust technique and does not require much expertise. This method always provides a diagnosis with a very low percentage of wrong diagnosis (95% accurate than any other method of diagnostics). Software implementation for Duval triangle can be done on the computer with many high level languages. Also, it is found from existing fault diagnostics tools for Indian conditions, the maximum fault occurring is T3 (44%).

For hotspot thermal test more accurate temperature measurement method is needed. A thermal camera could be used to film and measure the thermal distribution along the heating element of the power transformer. However, the way to deal with the blockage of test vessel need to be further studied.

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